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OSCILLATORY TRANSPORT COEFFICIENTS IN InAs SURFACE LAYERS

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ABSTRACT

The resistivity and Hall coefficient of gated n-InAs epilayers have been measured at low temperatures utilizing differential techniques and a magnetic field swept from zero to six tesla. When the InAs surface is in accumulation, three distinct series of oscillations, periodic in inverse magnetic field, are observed. These series are interpreted as the quantization of the surface electron energies into three subbands. The densities of these subbands are roughly linear in applied gate voltage and vanish as one approaches flatband. The temperature and magnetic field dependences of the oscillation amplitudes suggests an effective mass of .04 m_e and a Dingle temperature of 26K.

1. Introduction

Most surface quantization studies to date have been undertaken on inversion layers[1] in which case the surface transport can be isolated from that in the bulk. Accumulation layer transport studies have been less common. Tsui[2,3] however, has demonstrated the existence of surface quantization and characterized the behavior of the electronic energy levels in InAs surface accumulation layers using capacitance measurements and tunneling through a native oxide. At least qualitative agreement with several of the theoretical predictions of Baraff and Appelbaum[4] was found. Surface quantization in n-channel InAs inversion layers has been studied by Kawaji and Kawaguchi[5] who found an increase in mobility with carrier density, consistent with coulomb scattering in the quantized surface channel.

In this paper, we report on electrical transport measurements made on accumulation layers formed on the surface of InAs epitaxial films. To distinguish the surface contribution to the transport coefficients an MOS structure was employed and an excitation voltage was added to the dc gate voltage. The resulting differential signal was measured for both conductivity and Hall configurations as functions of gate voltage, magnetic field, and temperature. Three series of oscillations are observed and an analysis in terms of surface quantization in the accumulation layer yields information on the carrier effective mass and scattering lifetime which is compared to the bulk and surface parameters observed by others.

2. Experimental

The films of n-type InAs grown heteroepitaxially on GaAs have been described previously.[6] They are approximately 15 μm thick. Electrical measurements at

77K have found a bulk carrier density of about $2 \times 10^{15} cm^{-3}$, mobility of about $1.2 \times 10^5 cm^2/V\text{-}s$, and a front surface which is strongly accumulated.[7] A 1500 Å insulating SiO_2 layer covers the sample area and an aluminum gate completes the structure as shown in Figure 1. The flatband condition for

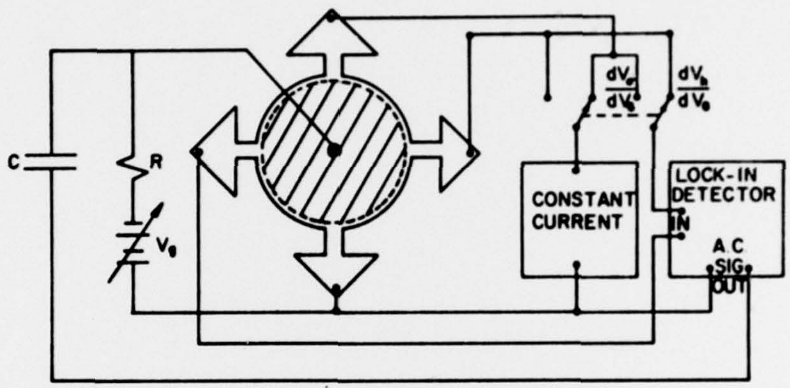

Fig. 1. Schematic of the sample and the measurement circuitry. The cross-hatched area on the sample represents the gate coverage.

this device occurs for applied electric fields near the break-down field of the insulator, thus precluding study of inversion layers. Two samples of this type have been measured. The one which yielded most of the data presented here has flatband condition occurring at $V_{FB} = -33$ V. This value comes from capacitance versus voltage curves which are essentially temperature independent from 4 K to 77 K. The total Hall coefficient for these films decreases[8] from 77 to 4 K, explained by our multi-layer analysis[7] as resulting from a decrease in bulk mobility. The bulk carrier concentration is, in fact, essentially constant between 77 and 4 K indicating the absence of freeze-out effects. Most measurements were made at 4 K with the sample immersed in liquid helium. The temperature was lowered by pumping on the helium and raised by heating the sample mount.

A constant current of 1.0 ma was passed through the InAs film and the voltage across the clover-leaf sample depicted in Figure 1 was measured in both the conductivity (V_σ) and Hall (V_h) configurations. These dc voltages exhibit oscillatory behavior as functions of gate voltage and magnetic field, but the amplitude is too small for reliable analysis. At T = 4 K and B = 6 T, for example, the oscillations were a maximum of 1% of the total and less than 10% of the change of the dc voltage from flat band to strong accumulation. Thus, a differential technique was utilized in which a 1 kHz signal of 0.1 or 0.2 V rms was added to the dc gate voltage. The sample voltage was fed into an Ithaco Dynatrac III lock-in amplifier using the vector sum mode resulting in the measured quantities $|dV_\sigma/dV_g|$ and $|dV_h/dV_g|$ (hereafter referred to as dV_σ and dV_h) as indicated in Figure 1. Lowering the ac frequency to as low as 20 Hz yielded no change in the experimental curves.

3. Results

Several curves of dV_σ and dV_h versus V_g were made using magnetic fields from 0.5 to 6 T. Two such curves for dV_σ at 4 K and 85 K are shown in Fig. 2b, which clearly indicates the low temperature nature of the oscillatory behavior. Curves similar to the 4 K one are reported by Wagner, et al.[9] The gate voltage dependence of the oscillations in Fig. 2b shows an onset on the accumulation side of the flat band voltage V_{FB}. V_{FB} = -33 V was obtained from an analysis[10] of the capacitance-voltage plot shown in Fig. 2a. The large long period peak seen in dV_σ at 85 K is expected from conductivity measurements[6,7] and is due to the decrease of mobility with increasing surface potential. The small peak near V_{FB} is more pronounced at 4 K and is similarly found in dV_h. Similar structure is seen in silicon MOS devices with field-effect mobility measurements[11] and is probably related to interface states. The temperature dependence of the oscillation amplitudes for both dV_σ and dV_h is shown in Fig. 3, and will be discussed in the following section.

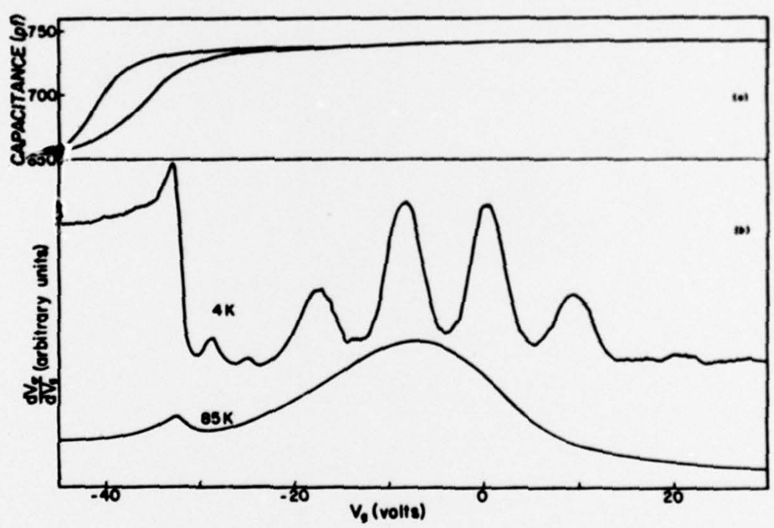

Fig. 2 (a) The capacitance-voltage plot taken at 77 K and B = 0. Flatband condition occurs at -33.3V. (b) Examples of $\frac{dV_\sigma}{dV_g}$ versus V_g experimental plots. Both curves are for B = 6 T, the bottom one being taken at 85 K and the top one at 4 K.

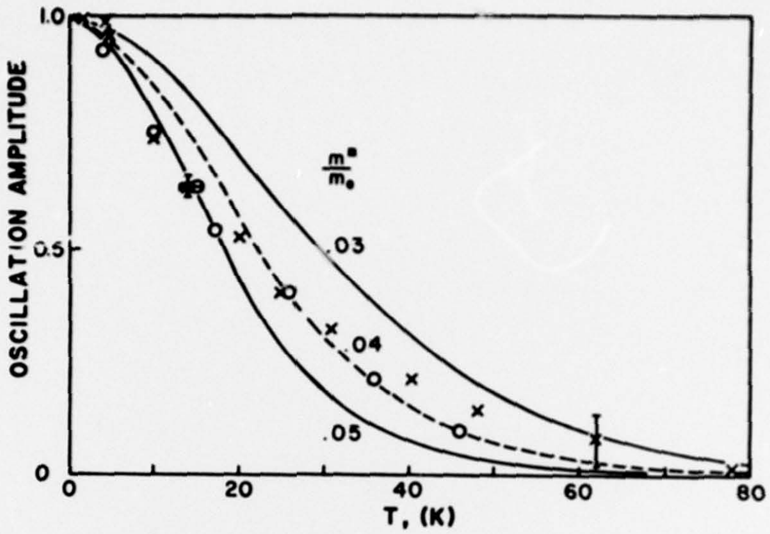

Fig. 3. Oscillation amplitudes versus temperature. The circles are obtained from $\frac{dV_\sigma}{dV_g}$ and the crosses from $\frac{dV_h}{dV_g}$ versus V_g plots at B = 6 T. The curves are calculated from Eqn (2) with the indicated values of effective mass. The data and curves are normalized to unity at T = 0.

Typical plots of dV_σ as a function of magnetic field are shown in Fig. 4. For $V_g > V_{FB}$ the plots consist of series of peaks which are periodic in 1/B. The identification of peaks corresponding to Landau levels of different subbands (see below) are indicated in the figure. Over the voltage range measured, three subbands are observed. The peaks at the higher fields and designated by (o) are assigned to the ground state subband Landau levels and peaks assigned to the first (x) and second (Δ) excited subbands are observed at correspondingly lower magnetic fields. This identification of peaks is aided by the construction of a graph similar to that used by others.[12] The peak positions obtained from dV_σ or dV_h versus V_g plots are

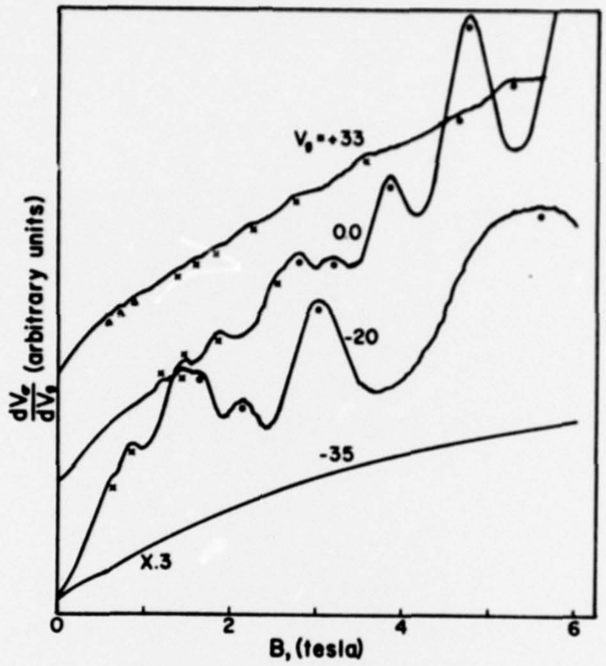

Fig. 4. $\frac{dV_\sigma}{dV_g}$ versus magnetic field at 4 K for various gate voltages. V_g = -35 V corresponds to near flatband. The peaks corresponding to the three subbands are identified by o-ground state subband, x-first excited subband, Δ-second excited subband.

put on a B versus V_g graph. Landau levels of different subbands are then seen to form well defined series of lines and by locating peaks in plots such as those shown in Figs. 4 and 5 on this graph, the particular subband can be identified. Since oscillations from different subbands have different

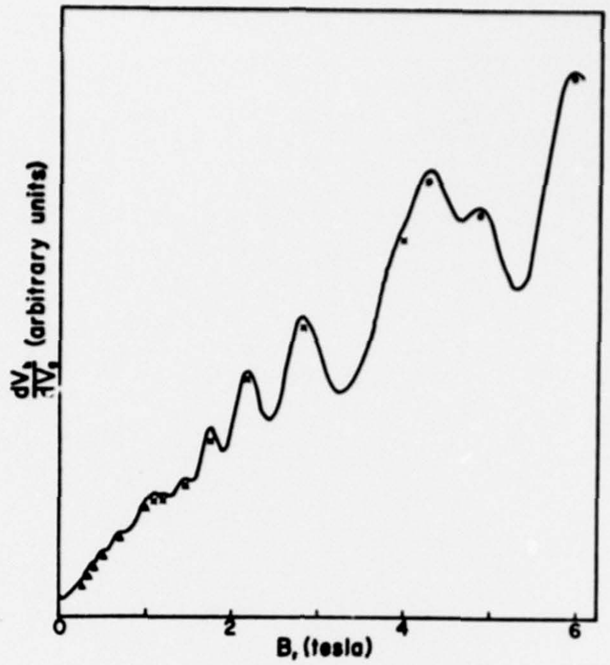

Fig. 5. $\frac{dV_h}{dV_g}$ versus magnetic field for V_g = +20 V. Peaks are labeled as in Fig. 4.

periods in 1/B and in V_g the superposition of Landau peaks from different subbands can also be distinguished. Perhaps the clearest indication of the three subbands is seen in Fig. 5 which shows the magnetic field dependence of dV_h for V_g = +20 V. This figure distinctly illustrates all three sets of oscillations with regions of overlap between the ground and first excited subbands occurring near 4 T and between the first and second excited subbands occurring near 1 T.

The second sample studied had a gate which covered less of the total surface area. It produced much the same structure in dV_σ as the sample here reported, but only two subbands were clearly distinguished and their densities at $V_g = 0$ were about 30% lower than those of the ground and first excited subband densities in the present sample. That sample did, however have clear indications of spin splitting beginning in the n = 0, 1, 2 Landau levels of the ground state subband at 5 T.

The principle difference between our results and those of Wagner et al.[9] is the absence in our data of a region between the ground levels and first excited levels where the oscillations disappeared. We also did not observe a measurable decrease in V_{FB} between 77 and 4 K. Comparison of different samples is difficult, however, because of the likelihood of variation in surface states and oxide charge.

4. Discussion

Since the InAs surface is strongly affected by surface states and trapped charge in the oxide[13], extraction of the subband energies and densities as a function of surface potential[4,14] would be somewhat speculative. The densities of carrie for each subband, however, can be obtained at a given gate voltage by using the theory of de Haas-van Alfen type phenomenon which results in the relation[2]:

$$N_i = \frac{e}{\pi\hbar\, P_i(1/B)} = \frac{4.84 \times 10^{14}}{P_i(1/B)} \ m^{-2} \qquad (1)$$

where $P_i(1/B)$ is the period of oscillation in $1/B$ (in units of T^{-1}) for a subband i, and N_i is the density of carriers per unit area. These densities have been calculated for the three subbands from plots like those in Figs. 4 and 5 and are plotted in Fig. 6 using averages of the dV_h and dV_σ plots. The dependence of density on gate voltage is linear to within the

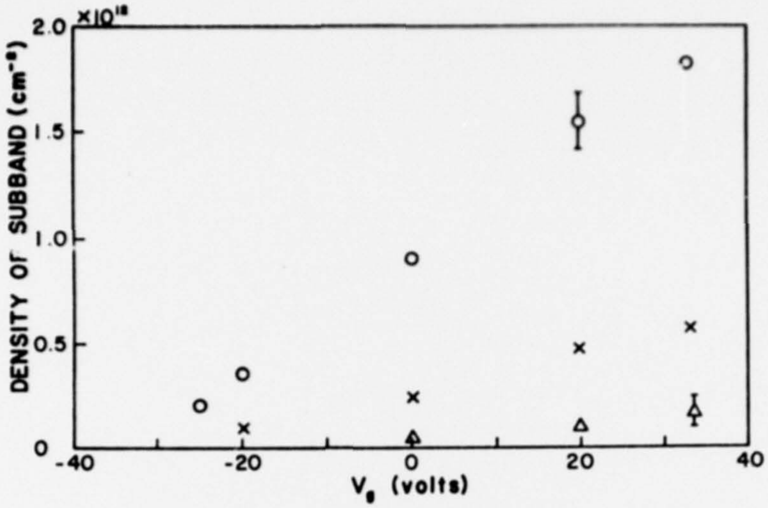

Fig. 6. Subband densities versus gate voltage at 4 K. The symbols identifying subbands are those used in Fig. 4.

experimental accuracy and the gate voltage intercepts corresponding to zero density are -32 ± 2 V, -29 ± 3 and -15 ± 8 V for the ground, first and second excited subbands, respectively.

The temperature dependence of oscillation amplitudes in magnetoresistance can be used to determine the effective mass.[15] Superimposed on our experimental results in Fig. 3 are the theoretical curves for different effective masses. The temperature dependence factor[15] should be

$$\text{Ampl.} \sim \frac{T}{\sinh\left[\frac{2\pi^2 kT}{\hbar\omega_c}\right]} \tag{2}$$

where $\omega_c = eB/m^*$ is the cyclotron frequency for electrons in the plane of the film. The oscillations analyzed for Fig. 3 resulted from the ground state subband at 6 T. All the curves were normalized to the same value at T = 0. It is seen that the effective mass ($\sim 0.04\ m_e$) is greater than the bulk value[16] of .024 m_e. Using the temperature dependence of magneto-resistance quantum oscillations, Sladek[17] found an apparent increase of effective mass for bulk InAs with increasing magnetic field with $m^* = .035\ m_e$ at 2.6 T, somewhat larger than predicted.[2] Tsui[2] found a cyclotron effective mass in surface layers of InAs from tunneling measurements which was about 10% larger than predicted for bulk InAs. He found masses in the range .025 to .032 m_e at 6 T for the Landau levels n = 0 to 2 of the ground state subband.

The onset of oscillations occurred at different magnetic fields for each of the three subbands. At comparable subband densities the first and second excited subbands required nearly equal fields to be observed, but the ground state subband required fields about two times larger. The condition for oscillations to be observed is $\omega_c \tau > 1$, where $\omega_c = eB/m^*$ and τ is the carrier scattering time in the surface layer. Assuming comparable effective masses for each of the subbands, this indicates scattering times are smaller for the ground state subband than for the excited levels. This is probably due to the ground state carriers being held closer to the surface.

The magnetic field dependence of the oscillation amplitudes can be used to determine the Dingle temperature.[15] Due to the superposition of peaks from different subbands an accurate determination of the amplitudes is difficult. However, for the ground state subband at $V_g = 0$ and $T = 4$ K the amplitudes did follow the expected $B^{\frac{1}{2}} \exp (2\pi^2 kT'/\hbar\omega_c)$ dependence and, assuming $m^* = 0.04\, m_e$, a Dingle temperature of $T' = 26$ K was determined. This compares to $T' = 16.9$ K found for bulk InAs at 4.2 K.[17] The larger Dingle temperature indicates a shorter scattering lifetime which is as expected for the surface layer. It is interesting to note that if this lifetime is associated with the momentum relaxation time involved in the surface mobility, a value of $\mu = 4 \times 10^3 cm^2/V$-sec is calculated which agrees fairly well with $\mu = 7 \times 10^3 cm^2/V$-sec found[7] at 77 K on a similar sample and thought to be nearly temperature independent.[8]

5. Conclusions

Oscillations in the conductivity and Hall voltages have been identified with carrier energy quantization in the surface accumulation layer of InAs. The three subbands observed have densities at $V_g = 0$ and $T = 4$ K of 9.5, 2.5, and $0.5 \times 10^{11} cm^{-2}$ which agree reasonably well with those found by Wagner, et al.[9] on similar samples. The temperature dependence of oscillations due to the ground level indicates an effective mass of about $.04\, m_e$ and the magnetic field dependence of the amplitudes indicates a Dingle temperature of 26 K.

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